Extractive Industries and Society, 2018, in press

Enabling food security through use of local rocks and minerals

David A C Manning

School of Natural & Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

david.manning@ncl.ac.uk

Suzi Huff Theodoro

Universidade de Brasília/ UnB, Postgraduate Program in Environment and Rural Development / PPG-MADER Brasília/DF. Brazil

suzitheodoro@unb.br

Abstract

In many developing countries, replacement of the nutrients needed to produce subsistence and cash crops is a major challenge, because of cost and long/complex supply chains. Nutrient audits show that major nutrients are being removed from soils faster than they are being replenished, which is clearly unsustainable. The use of crushed silicate rocks as a source of plant nutrients predates the use of the chemical fertilizers that have revolutionised global agriculture. Such highly soluble fertilizers are not ideal for the deeply leached oxisols widespread in the global south, and are rapidly leached. In these soils, silica may also need to be added as nutrient. In these circumstances, crushed silicate rocks have great potential to maintain soil health and to support crop production. In Brazil crushed rock remineralizers have been developed, and Brazilian federal law allows these to be used for crop nutrition, with specifications clearly defined by appropriate regulation. This approach provides a model that enables developing countries elsewhere to exploit local geological sources, and reducing dependency on imported chemical fertilizers. It creates opportunities for employment producing crushed rock products for different crops and locally variable soils and conditions, and illustrates renewed academic and practical interest in so-called 'Development Minerals.'

I. Introduction

The ability of soils to produce the food needed to support a global population expected to exceed 9 billion by 2050 is fundamental to sustainable development (Keesstra et al., 2016). Every crop removed from soil removes nutrients derived from the geological minerals present within the soil, and these need to be replaced, either by returning composted crop residues, manures etc, or by adding artificial fertilizers (Castellanos-Navarrete et al, 2015). Without careful husbandry, soils lose their ability to produce crops, threatening livelihoods at all levels and, more widely, the biodiversity of natural and managed (Brussard et al., 2007) ecosystems.

The importance of soil in economic development has been highlighted by Jeffrey Sachs (Sachs, 2003, 2005) as a key factor alongside disease and lack of infrastructure that needs to be addressed to support a population. More recently, this has been emphasised by Keesstra et al (2016) who analyse the role of soil science in addressing the Sustainable Development Goals, stressing the need for an interdisciplinary approach. Minerals and materials that are mined, processed, manufactured and used domestically, so called 'Development Minerals' (Franks et al., 2016) are receiving greater recognition for their role in structural economic transformation and poverty alleviation, with rock dust a potential pillar of this growing field (Hilson, 2016; Franks, 2017; Hinton et al., 2017).

Soil nutrient audits consider the balance between inputs and outputs, on a regional scale (Vitousek et al., 2009). Most consider N and P, with few addressing K. On a global scale, Sheldrick et al. (2002) considered N, P and K, highlighting the far greater deficiency in K compared with N and P. Despite their identification of the K deficit, few subsequent studies have addressed K, concentrating instead on N and P. Cobo et al. (2010) analyse nutrient use in Africa, at a range of scales. They confirm the conclusion that nutrient mining is a significant problem, whilst highlighting inconsistencies between published studies. Römheld and Kirkby (2010) emphasise the importance of K for crop (and animal and human) health, noting inconsistencies in current knowledge and approaches.

The price of fertilizers varies with time (World Bank, 2018; Figure 1). Since 2000, prices peaked for N and P fertilizers in 2008, when oil prices also peaked. The price of potash peaked later, in early 2009. In general, N fertilizer price is closely related to the oil price (Figure 2), reflecting the use of methane as a raw material in the Haber-Bosch process (Smil, 2001) as well as the energy cost of manufacture (Lægrid et al., 1999). The price of diammonium phosphate (DAP) also is highest when oil is highest, and between 2000 and 2018 the price of KCl was greatest (Figure 2) when Brent crude was cheapest. These price differences reflect the differences in production of NPK fertilizers, each of which has a very different supply chain. Since 2013, the price of potash fertilizers has remained constant for periods of several months, stepping up and down, to around $200/tonne at present, about twice the price at the start of the century. Such periods of constant price indicate a control that is independent of the price of oil.

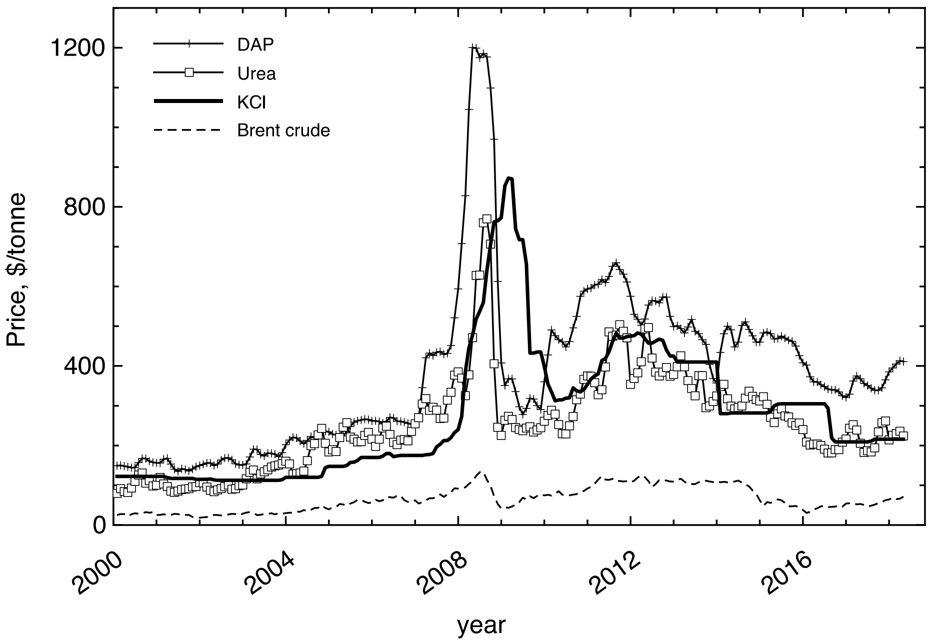

Figure 1. Variation in fertilizer prices, compared with oil (Brent crude) since 2000 (World Bank, 2018).

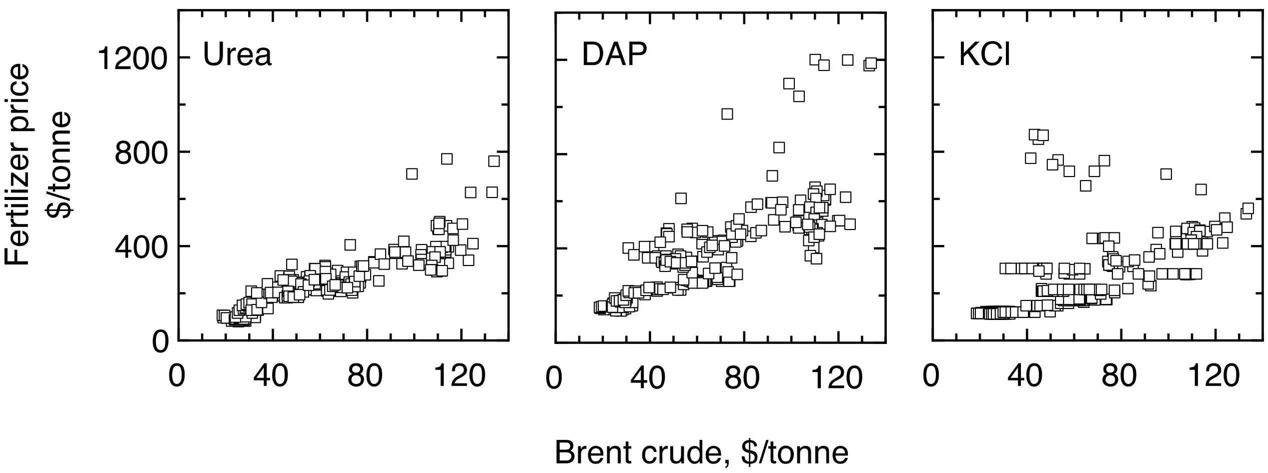

Figure 2. Variation in price of N, P and K fertilizers relative to price of Brent crude (2000-2018; World Bank, 2018).

The ability of soils to continue to produce a harvest depends on their nutrient status (if other factors are constant). The global use of fertilizers is recorded by the Food and Agriculture Organization of the United Nations (FAO, 2016). When analysed on a regional basis, inequalities in the use of fertilizers are readily apparent. Figure 3 shows per capita consumption, calculated using the aggregate populations (United Nations Population Division, 2017) for different regions as defined by the FAO. Approximate annual global consumption, per capita, for N is 13-16 kg, P (as P_2O_5) is 6 kg and K (as K_2O) is 4-5 kg, rising over time for most regions. Per capita, North America consistently consumes much more than the rest of the world, and South America more P and K (neither of which are mined significantly in that region). Central Europe consumes more N than other regions (apart from North America), but similar P and K. Regions which consistently show least consumption are Africa (N,P,K), East Asia (N), West Asia (P,K) and South Asia (K). Thus FAO figures show a major disparity in regional fertilizer use.

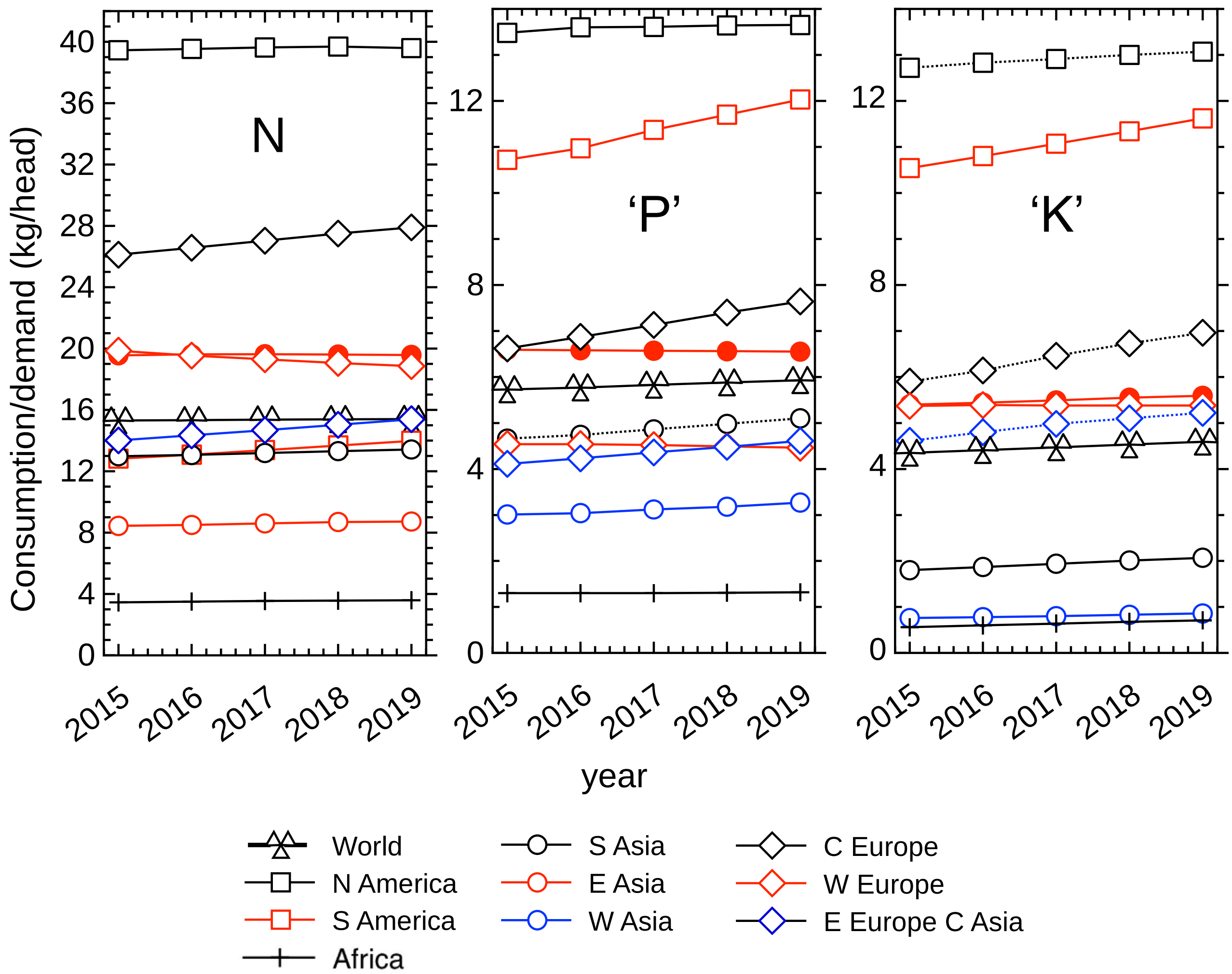

Figure 3. Regional use of fertilizers (data from FAO, 2016). 'P' denotes P_2O_5; 'K' denotes K_2O.

FAO figures have been recalculated to show proportions of consumption. In Figure 4, if the proportion of a region's population coincides with the proportion of fertilizer consumption, it plots on the 1:1 line diagonally crossing each graph. Consistently, North America and East Asia consume more than the proportion of population, and South America consumes more P and K. Consistently, Africa consumes less N, P and K than its population; South Asia and West Asia consume less K.

This approach to understanding demand for fertilizers represents a simplification of a complex situation. The use of conventional chemical fertilizers is part of a production model preferentially linked to agribusiness, which is directly related to the production of agricultural commodities. In South America (and especially in Brazil), fertilizer consumption is very high because the major countries of the region (Brazil and Argentina) are considered as agro-exporting countries, producing especially soybean, corn and wheat, all highly demanding of P and K. In Brazil, for example, according to data from ANDA (2016), about 65% of soluble fertilizers (NPK) are used for the production of three types of crop (soybean, corn and sugar cane).

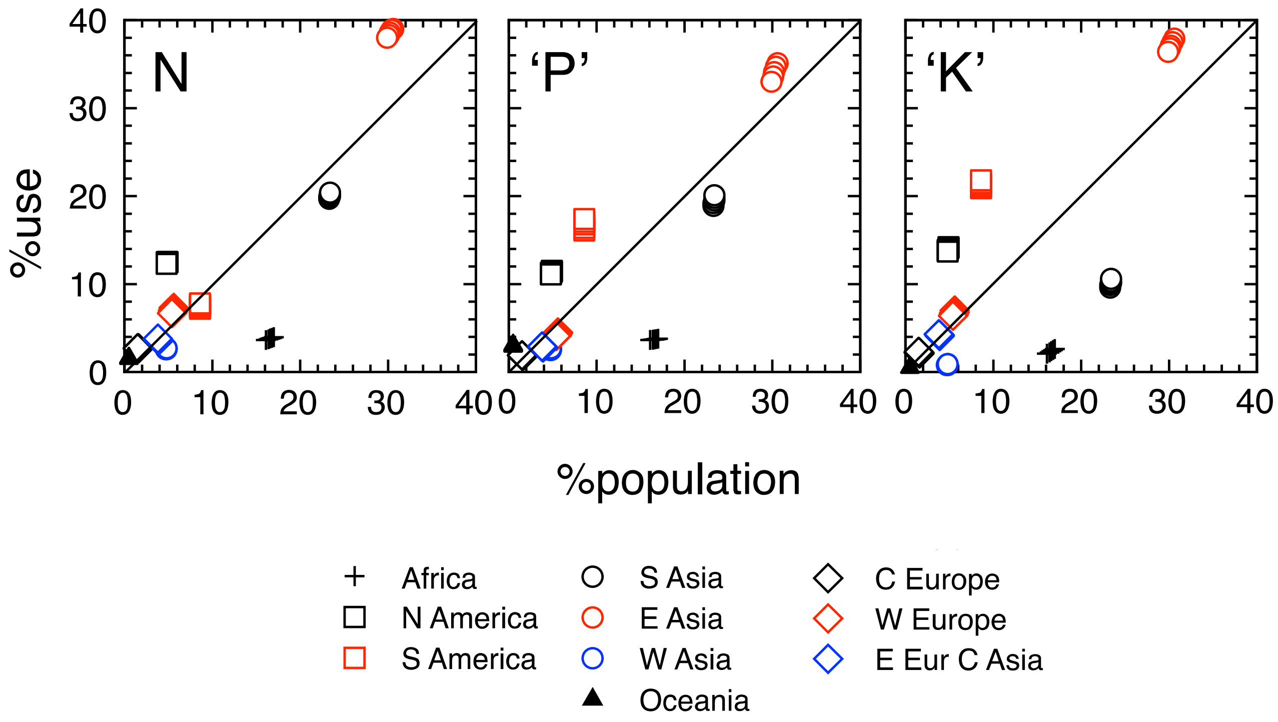

Figure 4. Fertilizer consumption comparing population and use (data from FAO, 2016). 'P' denotes P_2O_5; 'K' denotes K_2O.

Despite its limitations, the above analysis of price and use provides a global picture of inequality. In some regions, especially Africa, the use of fertilizers is far less than would be expected for a modern approach to agricultural production (Drechsel et al., 2001). Many factors contribute to this. Considering gender, Quisumbing and Pandolfelli (2010) state "*Although female heads of households uniformly apply less fertilizer than males, when farmer characteristics are controlled for in regression analysis, the critical factors that significantly limit fertilizer application are lack of access to credit and cash (Gladwin, 1992), not the sex of the farmer.*" Poor farmers in general, and particularly women, cannot afford fertilizers. In addition to poverty, which makes access to fertilizer resources difficult, women farmers are much more attached to the food and nutritional security of their families and, in many cases, consider that using the technological package (soluble fertilizers, agrochemicals and seeds) should be avoided. In the countries south of Ecuador, the number of women farmers who seek more agroecological alternatives (Siliprandi, 2014; 2018) is growing. Additionally, nutrient deficiencies, with consequences for human health, also reflect poor availability of trace nutrients in soils (eg Zn; Alloway, 2009).

In order to address these circumstances, alternative approaches to crop nutrition need to be considered (Horlings and Marsden, 2011). The primary goal is to enable farmers at the bottom of the economic ladder to produce crops first for subsistence and then for trade, enabling a greater number of people to participate in and benefit from modern agricultural methods. One approach is to use locally-obtained crushed rocks to supply a range of major and trace nutrients (van Straaten, 2009).

II. Geochemical background to use of crushed rocks

The use of crushed rocks as sources of crop nutrients is long-standing, if not widespread. Driven by necessity (Ciceri et al., 2015), Goldschmidt, the father of modern geochemistry, investigated the use of nepheline syenite as a source of K for the US and UK at a time when Germany dominated production and controlled international trade (Goldschmidt, 1922; Goldschmidt and Johnsen, 1922). Leonardos et al (1987) proposed the use of silicate rocks as sources of crop nutrients for lateritic soils, emphasising the differences between these and temperate soils, and the implications for nutrient management. In lateritic soils, silicate minerals are demonstrably unstable, as these soils are dominated by the presence of oxy-hydroxide minerals and clays produced by silicate mineral weathering. In contrast, temperate soils contain a range of silicate minerals predominantly produced by mechanical weathering of the parent rock. Modern chemical fertilizers are designed for use in these, taking advantage of cation exchange as well as relatively low levels of leaching. However, they are rapidly leached from lateritic tropical soils, which generally have lower cation exchange capacities.

Plants require nutrients to be present in the soil solution, so that they can be taken up by roots. The soil solution derives its mineral nutrients ultimately from two sources: the geological minerals that are naturally present in the soil, or from artificial chemical fertilizers, which include salts that are relatively soluble. The geological minerals that provide the major soil nutrients are dominated by silicates, including micas, and these have a relatively low solubility. The mechanisms by which nutrients are released to enter the soil solution and so become plant-available include weathering (in which the original silicate mineral structure is destroyed) and cation exchange, in which the structure is preserved, and cations are exchanged between the mineral and the soil solution. Weathering of aluminium-bearing silicate minerals typically produces aluminous clay minerals, reducing Al in solution to minimum values around neutral pH.

Silicate mineral weathering is well known but poorly quantified (White and Brantley, 1995), and is essential for growth given the role of silica in plant metabolism (e.g. Keeping, 2017). In general, the long-standing empirically observed weathering sequence (Goldich, 1938) indicates the relative stabilities of the common rock-forming minerals. The thermodynamic basis for Goldich's observations was provided by Curtis (1976); the weathering sequence closely corresponds to the inherent thermodynamic stability of the minerals, and so is predictable. However, more information is needed to predict the ability of a silicate mineral to release nutrients to the soil solution, so that they become available to plants. The kinetics of the mineral dissolution reactions control nutrient availability. These relate to the mineral's surface area and are normally expressed as moles per metre squared per second and vary by several orders of magnitude (Palandri and Kharaka, 2004). Table 1 gives examples of silicate mineral dissolution rates, expressed at standard conditions of 25°C and pH 0 to allow comparison.

Importantly, the data shown in Table 1 have two messages. First, dissolution rate is not necessarily greatest when the content of an element of interest, such as K, is highest. Nepheline contains about 25% the K content of K-feldspar, but has a dissolution rate that is several orders of magnitude greater. Anorthite has a Ca content smaller than wollastonite, and dissolves 60 times more quickly. Secondly, the dependency on surface area shows the benefit of fine grinding (e.g. Priyono and Gilkes, 2008), and (importantly) the need to know the surface area of mineral treatments used in experimental work, taking this into account when comparing different studies.

Mineral family	Mineral	Formula	Releases	Typical content	Dissolution rate mol.m^{-2}s^{-1}	Relative dissolution rate
Potassium silicates						
K-feldspar	Orthoclase	$KAlSi_3O_8$	K	14.1	-10.06	1
Feldspathoid	Leucite	$KAlSi_2O_6$	K	17.4	-6.00	11,500
Feldspathoid	Nepheline	$(Na,K)AlSiO_4$	K	4.2	-2.73	21,400,000
Mica	Muscovite	$KAl_3Si_3O_{10}(OH)_2$	K	9.1	-11.85	0.016
Mica	Biotite	$KMg_3AlSi_3O_{10}(OH)_2$	K, Mg	7.5, 3.6	-9.84	1.66
	Glauconite	$K(Fe^{3+},Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$	K, Mg	7.5, 3.0	-4.80	182,000
Other silicates						
Plagioclase	Anorthite	$CaAl_2Si_2O_8$	Ca	13.6	-3.50	3,630,000
Plagioclase	Albite	$NaAlSi_3O_8$	Na	8.7	-10.16	0.794
Olivine	Forsterite	Mg_2SiO_4	Mg	33.6	-6.85	1,620
Pyroxene	Wollastonite	$CaSiO_3$	Ca	33.6	-5.37	49,000
Pyroxene	Diopside	$CaMgSi_2O_6$	Ca, Mg	18.6	-6.36	5,010
Pyroxene	Enstatite	$Mg_2Si_2O_6$	Mg	35.0	-9.02	11
Amphibole	Hornblende	$Ca_2(Mg,Fe)_4Al[Si_2AlO_{22}](OH)_2$	Ca,Mg	8.6, 7.8	-7.00	1,150
Tourmaline	Dravite	$NaMg_3Al_6B_3Si_6O_{30}(OH)$	Mg, B	7.8, 3.5	-6.50	3,630

Table 1 Silicate mineral dissolution rate constants (25°C, pH = 0; Palandri and Kharaka, 2004). For comparative purposes, relative dissolution rates express the dissolution rate of a mineral relative to that of K-feldspar.

Silicate rocks can be processed to yield concentrates of specific minerals, either as an intended product or a by-product (eg Bakken et al., 2000). This potentially adds cost, although it is a useful way of approaching a target of generating zero waste from a mine, delivering all mined material as a product. Without processing, use of crushed rock as a source of nutrients is an alternative route to nutrient supply. Given that crushed rocks typically contain more than one rock-forming mineral, a bulk dissolution rate needs to be determined that takes into account (a) the minerals that are present and (b) their intergrowths and textural relationships. A general predictive model of element release from crushed rocks is a challenging task.

III. Experience in use of crushed rocks

A number of studies have investigated the ability of silicate minerals and rocks to supply nutrients for crop growth. In the UK and Sweden, some have shown little if any response by plants to treatment with crushed volcanic rock (e.g. Ramezanian et al., 2012). Other studies have shown a positive response (e.g. Bakken et al., 2000). In detail, these contrasting results arise for mineralogical reasons. Bakken et al (2000) used a crushed rock that included nepheline; this has the highest dissolution rate of the silicate minerals listed in Table 1, and so might be expected to deliver K when exposed to a soil. Ramezanian et al (2012) use a volcanic rockdust (pyroxene andesite), with a much coarser grain size distribution (Mohammed et al., 2014). This was applied to soils that in some cases contained the same minerals as the treatment – and, not surprisingly, no effect was observed. Mohammed et al (2014) took care to use natural soils that did not contain the same mineral as the treatment, and a response to the application of K silicate minerals was observed. Using artificial soils made from a high purity silica sand, Manning et al. (2017) showed that it was possible to demonstrate that plants are able to access K from a K-silicate mineral treatment, provided care was taken to ensure that the soil lacked other sources of K.

Other studies have investigated treatment with K-bearing silicate rocks (Manning, 2010; Harley and Gilkes, 2000). Many experiments in Europe and Australia have shown that application of crushed rock fails to provide K required for crop growth, in that statistically significant differences are usually lacking. Manning (2010) reviewed 20 reports of 13 pot/9 field trials relating to K, involving 16 crops and 7 different K-bearing silicate rock types. 13 of these reported benefits, either as increased crop yield or increased K availability. In the absence of a consistent approach from one study to another, it is difficult to take these results further to provide general conclusions.

Overall, for soils in which silicate minerals already occur, like those dominating in temperate zones, with a few exceptions, peer-reviewed experimental studies have yet to demonstrate unambiguously that treatment with crushed silicate rocks gives an agronomic benefit. Yet in practice farmers observe benefits and continue to use these materials. In contrast, there is an increasing amount of information from studies carried out in Brazil, following early identification of the potential of crushed silicate rocks in tropical soils (Ilchenko, 1955; Guimarães,1955; Leonardos et al., 1987; 2000). Most recently, Tavares et al. (2018) demonstrate the beneficial effect of application of compost-phonolite mixtures for pasture. Guelfi-Silva et al. (2013) compared a range of crushed rocks (milled, <3mm), including an alkaline volcanic breccia, containing feldspathoids, zeolites and volcanic glass, an alkaline ultramafic rock containing olivine, pyroxene, phlogopite, plagioclase and carbonate), two different biotite schists, containing biotite and quartz, a phlogopite rock, containing phlogopite and serpentine, and a by-product of manganese mining), with positive results for growth of lettuce in a Latosol. Santos et al (2016) evaluate 'verdete' (<150 microns), a metamorphic schist containing glauconite (a mica) and K-feldspar on growth of maize, grass and eucalyptus in pots, for Typic Hapludox soil. Without pretreatment of the 'verdete', no benefit was seen. If calcined or acidified, agronomic benefits were observed, as these chemical treatments increased K availability. Ramos et al (2017) consider volcanic rock waste, assessing the availability of nutrients using leaching tests but without plant growth experiments. Theodoro and Leonardos (2014) tested five types of rocks (fresh and weathered basalt, kamafugite, carbonate schist and biotite gneiss) mixed (or not) with an organic source. They verified that the availability of P, K, Ca and Mg increased in the soil, as compared to the control plots, one year after the application of the remineralizers. They further showed that remineralizers (mixed or not) with an organic source increased the pH and cation exchange capacity values. The study also revealed that the production of five agricultural crops was better following the second harvest, which may indicate that the solubility (and nutrient supply) increases over time, with the interaction of the geological material in the soil and the organic acids produced by roots. In other tropical systems, Anda et al (2009) demonstrate the value of crushed basalt for improving the cultivation of cocoa on an oxisol (SE Asia; Rhodic Hapludox). In India, Nishanth and Biswas (2008) showed the benefit of treatment based on a mixture of low grade phosphate rock and muscovite for wheat production (Typic Haplustept soil), and Meena and Biswas (2014) for microbial biomass and other soil parameters.

In Brazil, since the 1990s and particularly in the beginning of the 21st century, interest in using crushed rocks to remineralize soils has increased, and has led to the formation of the Rochagem movement. The need for alternative sources of crop nutrition arises from concerns about environmental issues and rising fertilizer prices, giving Brazil's dependency on imports. The major commodity crops (sugar cane, soybeans, maize, cotton, coffee beans, rice) are produced from 76% of the country's agricultural land, representing 10% of rural properties. Production of vegetables for sale to consumers (e.g. maize, beans, cassava, herbs and greens) is from 24% of the country's land, with 90% of rural properties. This sector is dominated by small farmers, who find access to fertilizers difficult because of cost as well as other factors. The Brazilian Federal Government has taken steps to encourage small farmers to use more fertilizers, and to regulate alternatives, to broaden the options available to this sector.

Access and use of conventional NPK formulations is strongly connected to a country's sovereignty. Brazil is a typical example of this because, despite being the fourth largest fertilizer consumer in the world (over the last 10 years it has imported about 70% of what it consumes), it is one of the largest commodity producers globally (particularly soybeans; ANDA, 2016). This characteristic can be interpreted in at least two ways. In the first, Brazil remains a strong agroexporter of commodities, and in the second, its sector of greatest economic success is weakened as a result of the need to import a large part of the input it consumes in order to continue producing. This weakness opened up a space for discussing new technological paths, among which are the use of soil remineralizers. These alternatives should be able to, simultaneously, have a positive change on the low index of fertile tropical soil (which is highly weathered) and present results, in terms of productivity, that are compatible with what farmers expect.

IV. The Rochagem movement in Brazil

In Brazil the Rochagem movement has been instrumental in making change that enables crushed rocks to be used as remineralizers. It dates back to pioneering work carried out in the 1950s (Ilchenko, 1955; Guimares, 1955). In the 1970s, Leonardos et al (1976) and Fyfe and Leonardos (1978) proposed the use of volcanic rocks to recover soil fertility. This took place against the background of the 'green revolution', that influenced agricultural policy in many countries, especially in Brazil, involving the use of agrochemicals, improved seeds, and mechanization. At that time, alternatives to this model were ignored by policy makers.

However, although it is unquestionable that this model of agricultural production was successful, in terms of productivity, it has not fulfilled its principle promise, to end the world's hunger. On the contrary, it has favoured the production of commodity crops in preference to food crops traded for day-to-day consumption. Other associated problems have developed, with increased land degradation and the continued exclusion of small, family-based, non-industrial agricultural units. In these circumstances, research into the use of rock powders deserved to be considered. Towards 2000, research at the University of Brasilia demonstrated the value of ultra-potassic kamafugites for the production of corn, sugar cane and manioc by farmers settled as part of the Program of Agrarian Reform. This pioneering research demonstrated the need to form a network of researchers to test the approach more widely in Brazil. At the same time, the Brazilian national agricultural research organization, EMBRAPA, started research into the use of powdered rocks as an alternative to the use of imported chemical fertilizers, because of their high price.

This coincidence of interests led to the organization in 2004 of the first international conference "Rocks for Crops' in Brasilia, with the participation of scientists and researchers from 5 continents, representing Indonesia, Canada, Kenya, Japan and Portugal, as well as Brazilians already convinced of the potential national importance of Rochagem. This conference considered the regulation of rock powders in Brazil, and practical aspects of how rock powders would become part of Brazilian agriculture. Three years later, in 2007, the second Rocks for Crops conference took place in Kenya, with the participation of Brazilian researchers who presented new results from studies in Brazil.

An important outcome of these conferences, to improve consistency and to build on doctoral and masters theses, was the need to establish in Brazil an Interinstitutional Working Group (Grupo de Trabalho Interinstitucional - GTI) composed of researchers and technical experts from the Government, involving the Ministries of Science and Technology, Mines and Energy, and Agriculture, with universities, the Brazilian Geological Survey, Petrobras, the National Mining Agency and EMBRAPA. This group organized the First Brazilian Congress on Rochagem in 2009

(Martins e Theodoro, 2009). At this event, the results of around 60 scientific studies were presented, by Brazilian scientists and international guests. The Second Brazilian Congress on Rochagem was held in 2013, with participants from 15 universities, six countries and representatives from the minerals industry. The conference proceedings contain around 70 papers (Theodoro, et al., 2013). One of the key themes discussed at this event was the establishment of parameters that could be used to define the permitted characteristics and guaranteed minimum specifications that would enable the use of remineralizers to be regulated. The Third Brazilian Congress on Rochagem was held in 2016, with around 80 scientific contributions (Bamberg et al., 2016).

Combined, these studies demonstrated positive results from the use of rock powders as remineralizers, including: (i) the costs of acquiring rock remineralizers are significantly less (up to 80%); (ii) a single application can be effective for up to four or five years; (iii) in remineralized soils, fertility levels have been increasing (particularly the levels of P, K, Ca and Mg) over the last five years; (iv) productivity is similar to or higher than conventional fertilization (it can yield up to 30% more return than for systems that use chemical inputs); (v) plant roots are better developed than those of plants which receive chemical fertilization, most probably due to the higher nutrient levels and reduced aluminum toxicity and pH correction; (vi) the level of soil moisture is higher in areas where remineralizers are applied, showing that they retain large amounts of water; (vii) plants show a higher amount of green mass, they are more abundant and have greater tillering; (viii) the plant’s productive cycle was accelerated in some cases; (ix) there was no contamination or eutrophication of water sources because the rock dust has a gradual solubility, contrary to conventional fertilizers; and (x) it meets the standards of guarantee required of inputs used in organic agriculture, which as a sector has an average annual growth rate of 35% (Leonardos and Theodoro, 1999; Theodoro and Leonardos 2006; 2014; Souza et al. 2018; Melamhed, et al, 2009; Almeida et al, 2006)

Despite the many positive results presented in conferences, there was until recently no draft for a formal protocol that could enable use, commercialization or regulation of ground rock soil remineralizers since, due to their diverse characteristics, it was not possible to include them within existing input categories (conditioners, fertilizers, etc.). Changing this gap in regulatory rules was a fundamental factor in the viable use of remineralizers.

In order to change this situation, the interinstitutional working group developed a proposal which was presented to the Brazilian legislature. The proposal was the culmination of discussions held in national conferences, seminars and workshops on the proposal between the mineral sector and the agriculture sector. This group came to the conclusion that the needs of the mineral sector to develop new applications, in appropriate cases, for large amounts of residue resulting from mineral extraction could be converted into a solution for agriculture as long as a few careful measures were taken, such as: (i) a lack of contaminants in the crushed rock; (ii) having the main macro and micronutrients in the rock minerals; and (iii) the availability of the source close to the consumption area.

The Working Group suggested that a congressman present a Bill to the Federal Senate which would include remineralizers in the Fertilizer Law (Law 6.894/1980). The congressmen understood that this was an important issue that affected the sovereignty and development of the agriculture sector in Brazil. Additionally, the international fertilizer market did not believe that this proposal could have a strong impact on consumer demand. The few reactions to this were mainly local, particularly because the potential consumers of these products were mostly family agriculturists. The proposal to include rock dust as a category of agriculture input stated that remineralizers "*are material of mineral origin whose size has been reduced and classified by mechanical processes* *alone, its soil fertility indices altered through the addition of macro and micronutrients to the plants which also helps to improve the physical and physical-chemical properties or the biological activity of the soil".*

The proposal was approved and passed relatively quickly in Brazilian National Congress (around 16 months). In October 2013 it became known as Law 12.890 (Brazil, 2013). Subsequently, a decree was issued (Decree 8.384/2014) along with two Normative Instruction (INs) establishing minimum requirements that remineralizers must meet in order to be recognized by Brazilian regulation. The Instruction, IN 05 and 06 (Brazil, 2016), established the regulations for defining, classifying, specifying and guaranteeing, tolerances, registering, packaging, labelling and marketing the remineralizers used for agriculture.

This legal framework brought security and an increased interest on the part of Brazilian agriculturists (including major soy producers) because it deals with an input which is available locally/regionally, it is significantly cheaper and because the productivity is comparable to that of regional averages. It sets out clear requirements for these materials to rebuild soil fertility and to maintain crop production, in systems where conventional chemical fertilizers might be inaccessible on the grounds of cost, or in organic systems where chemical products cannot be used (Abbott and Manning, 2015). At present, a snapshot view of the on-line retail market (e.g. http://www.mfrural.com.br) in Brazil shows that a number of different 'pós de rochas' products (rock dust) are available at quoted prices from R$60-350 (US$15-90) per tonne.

Another positive point relating to the use of rock powders as remineralizers in Brazil concerns the role played by the country's minerals sector, which is a major exporter of metals, especially iron. The extractive industries represent 4.3% of the entire domestic productivity of Brazil, and 16.9% of industrial production (IBRAM, 2018). At present, according to data from the National Mining Agency, there are 3354 mines active in Brazil, of which 5% (159) are large, producing >1million tonnes per year, and 25% (837) are intermediate, producing 100 thousand-1million tonnes per year. The great majority, (70%; 2358 mines) are small, producing less than 100000 tonnes per year, often open pits that produce construction and civil engineering raw materials. These are distributed widely across Brazil, providing great potential for the development of new products targeted at agricultural markets. Many of these businesses produce materials that meet the requirements of Lei 12.890/2013, including basalt, slate/shale and granites.

After the implementation of this law, many businesses showed an interest in registering with the Ministry of Agriculture, Livestock and Supply to enable them to commercialise their products as remineralizers. Obtaining registration has been a slow process, because the applicants must demonstrate, through research and analysis, that their product is effective agronomically. Until now, according to information from the Ministry, there have been around ten successful registrations. It is hoped that this number will increase in the next few years, given the increasing interest from conventional agriculture in the use of these inputs.

In addition, the National Policy of Organic Production (Política Nacional de Produção Orgânica; PNAPO; Brazil, 2003) allows the use of rock powders in organic production systems, by means of Instrução Normativa Nº 46, de 6 de outubro de 2011 (Anexo V; Brazil 2011). Considering that demand for organic products is increasing by 30% annually, it is expected that use of appropriately regulated rock powders as remineralizers will increase in these systems.

At this time, it is not possible to estimate the number of agricultural producers who use remineralizers in Brazil. There is no formal statistical indicator of their use, but it is evident that demand is growing, as experience shows that application of these geological materials improves the fertility of Brazil's tropical soils.

V. Implications for development

The scientific basis for the use of crushed silicate rocks as sources of crop nutrients is growing in extent, and explains why different results have been reported by studies in different parts of the world. The Brazilian experience, which has led to formal recognition by government of farmers' desire to use these materials and the development of an appropriate regulatory framework, has implications for developing countries elsewhere in the world, and also for the developed world.

Translation of what has been learnt in Brazil to Africa has already started. Theodoro et al (2012) describe a collaboration between Angola, Cameroon and South Africa, which enables a South-South research network to facilitate transfer of knowledge from Brazil and vice versa. More widely, acceptance of rock dust for soil remineralization in Brazil provides an example of a regulatory framework for other countries. Use of rock dust as a source of K, for example, is reported in studies from a range of countries and soil types (Manning, 2010), but with variable results. A re-evaluation of these studies in the light of the theoretical understanding of the dissolution of silicate minerals in soils allows greater insight into how they might be used, and improved design of field and pot experiments, to ensure that these genuinely reflect the role of the treatment.

The focus on nepheline-bearing rocks as a source of K has immediate relevance for areas close to the East African Rift System (EARS). This is characterised by the presence of nepheline syenites and related rocks, extending from Malawi to Ethiopia. Countries along the EARS include some of the poorest in the world, and so identification of nepheline syenite as an indigenous source of K may well be beneficial. If a regulatory system like that of Brazil is adopted by other countries, to ensure safe use of mined materials, farmers have a new option for maintaining soil fertility. The experience of using nepheline syenites as a source of K, documented in peer-reviewed research papers, is long-standing (Goldschmidt 1922; Goldschmidt and Johnsen, 1922) and is extended by the modern results reported by Bakken et al (2000) for Norwegian nepheline syenite, and also for Brazilian phonolite (Tavares et al., 2018; Theodoro et al., 2012; phonolite is a fine grained variety of nepheline syenite).

In the global north, use of crushed rock (rockdust) is accepted for remineralization in organic and some conventional production systems. This approach aligns with 'agroecology', the desire to approach agricultural production in a holistic way, so that food production is not in conflict with other important ecosystem services. The concept of geotherapy is articulated by several authors in Goreau et al (2014), and the UK's 25 year plan 'A Green Future: Our 25 Year Plan to Improve the Environment' (DEFRA, 2018) sets a direction of travel that emphasises the importance of an integrated approach to farming and ecosystem management. This approach has much to learn from Brazil and the global south, where where opportunities to access economic and industrial resources have driven the need to use alternatives to chemical fertilizers.

VI. Conclusions

The need in Brazil to find alternative sources of crop nutrition that are available to small farmers, who produce the majority of non-commodity crops, has led to the development of a clear regulatory framework that enables crushed silicate rocks to be used in circumstances where conventional fertilizers are inaccessible, on the grounds of costs or logistics. Given that many silicate rocks contain the nutrients required for plant growth, and occur widely, Brazil's approach is applicable in many developing countries, especially those with deeply leached tropical soils. The mechanisms by which crushed rocks release nutrients depend on dissolution rates of their constituent minerals, rather than the content of the nutrient of interest. Once this is considered, experiments to determine their efficacy can be designed and interpreted consistently. Wider use of crushed silicate rocks provides one route to development especially of the agricultural sector that produces crops for local markets. This approach enables farmers who cannot afford conventional fertilizers to have an alternative, and particularly supports female producers. In addition, this technological route can increase the potential of agro-ecological agriculture, which is in agreement with a search for a more sustainable world, where food security is a determinant axis of development.

VII. Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

VIII. References

Abbott, L. K. and Manning, D. A. C. (2015) Soil health and related ecosystem services in organic agriculture. Sustainable Agriculture Research, 4, 112-121.

Alloway, B. J. (2009) Soil factors associated with zinc deficiency in crops and humans. Environmental Geochemistry and Health, 31, 537–548.

Almeida, E., Silva, F. J. P. and Ralisch, R. (2006) Powdered rock to revitalize soils. LEISA Magazine, 22, n. 4.

ANDA – Associação Nacional para a Difusão de Adubos – Anuário Estatístico (2016) http://anda.org.br/index.php?mpg=03.00.00, Accessed 18th September 2018.

Anda, M., Shamshuddin, J., Fauziah, C. I. and Omar, S. R. S. (2009) Dissolution of ground basalt and its effect on oxisol chemical properties and cocoa growth. Soil Science, 174, 264–271.

Bakken, A.K., Gautneb, H., Sveistrup, T. and Myhr, K. (2000) Crushed rocks and mine tailings applied as K fertilizers on grassland. Nutrient Cycling in Agroecosystems, 56, 53-57.

Bamberg, A. L., Silveira, C. A. P., Martins, E. de S., Bergmann, M., Martinazzo, R. and Theodoro, S. H. (2017) Anais do III Congresso Brasileiro de Rochagem, Pelotas, 2016. Embrapa Clima Temperado, Pelotas; Embrapa Cerrados, Brasilia, 455 pp., ISBN: 978-85-61175-68-9.

Brazil (2003) Lei nº 11. 10.831, de 23 de dezembro de 2003 - Política Nacional de Produção Orgânica PNAPO, 2003. http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Decreto/D7794.htm (Accessed 18th September 2018).

Brazil (2016) Instrução Normativa Nº 05 de 10 de março de 2016 http://www.agricultura.gov.br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/in-5-de-10-3-16-remineralizadores-e-substratos-para-plantas.pdf (Accessed 18th September 2018).

Brazil (2013) Lei 12.890/2013 de 10 de dezembro de 2013 - Altera a Lei no 6.894, de 16 de dezembro de 1980. https://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/lei/l12890.htm (Accessed 18th September 2018).

Brussard, L., de Ruiter, P. C. and Brown, G. G. (2007) Soil biodiversity for agricultural sustainability. Agriculture, Ecosystems and Environment, 121, 233–244

Castellanos-Navarrete, A., Tittonell, P., Rufino, M. C. and Giller, K. E. (2015) Feeding, crop residue and manure management for integrated soil fertility management – A case study from Kenya, Agricultural Systems, 134, 24-35.

Ciceri, D, Manning, D. A. C. and Allanore, A. (2015) Historical and technical developments of potassium resources. Science of the Total Environment, 502, 590–601.

Cobo, J. G., Dercon, G. and Cadisch, G. (2010) Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress Agriculture, Ecosystems and Environment, 136, 1–15.

Curtis C.D. (1976) Stability of minerals in surface weathering reactions: a general thermochemical approach, Earth Surface Processes, 1, 63–70.

DEFRA (2018) A Green Future: Our 25 Year Plan to Improve the Environment, https://www.gov.uk/government/publications/25-year-environment-plan (Accessed 18th September 2018).

Drechsel, P., Gyiele, L., Kunze, D. and Cofie, O. (2001) Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa. Ecological Economics, 38, 251–258.

FAO (2016) World fertilizer trends and outlook to 2019. Food and Agriculture Organization of the United Nations - Rome, 2016.

Franks, D.M., Pakoun, L., Ngonze, C. (2016). Development Minerals: Transforming a neglected sector in Africa, the Caribbean and the Pacific. United Nations Development Programme. http://www.developmentminerals.org/images/pdf/Report_Showcase_Event_EN.pdf (Accessed 6th November 2018).

Franks, D. M. (2017). Reconsidering the role of minerals and matter in international development. Bryan Lovell Meeting 2017: Mining for the Future. p.22-23. The Geological Society, London. https://www.geolsoc.org.uk/~/media/shared/documents/Events/2017/BL17%20abstract%20book.pdf (accessed 6th November 2018).

Fyfe, W. S. and Leonardos, O. H. (1978) Global tectonics and resources for man: minerals and agriculture. Jornal de mineralogia. Volume Djalma Guimarães, Recife, 7, 51 - 58.Gladwin, C. (1992). Gendered impacts of fertilizer subsidy removal programs in Malawi and Cameroon. Agricultural Economics, 7, 141–153.

Goldich S. S. (1938) A study in rock weathering, Journal of Geology, 46, 17–58.

Goldschmidt, V. M. (1922). Oversikgtskart over utbredelsen av de forskjellige kalimineraler I norsk fjeldgrund. Norsk Landmansblad, 41, 268-269.

Goldschmidt, V. M. and Johnsen, E. (1922). Glimmermineralernes betydning som kalikilde for planterne. Norges Geologiske Undersøkelse Bulletin, 108, Trondheim, 89pp.

Goreau, T. J., Larson, R. W.; Campe, J. (2014) Geotherapy: Innovative methods of soil fertility restoration, carbon sequestration and reversing CO_2 increase. CRC Press. USA. p. 5-57.

Guelfi-Silva, D. R., Marchi, G., Spehar, C.R., Guilherme, L. R. and Faquin, V. (2013) Agronomic efficiency of potassium fertilization in lettuce fertilized with alternative nutrient sources. Revista Ciência Agronômica, 4, 267–277.

Guimarães, D. (1955) Contribuição ao estudo dos Tufos da Mata da Corda. Inst. Tecnol. Industrial, Minas Gerais. 31p.

Harley, A. D. and Gilkes, R. J. (2000). Factors influencing the release of plant nutrient elements from silicate rock powders: a geochemical overview. Nutrient Cycling in Agroecosystems, 56, 11-36.

Hilson, G. (2016). Development Minerals in Africa, the Caribbean and the Pacific: Background Study. In Franks, D. M., Pakoun, L. and Ngonze, C. (series editors), 'Development Minerals in Africa, the Caribbean and the Pacific'. ACP-EU Development Minerals Programme, United Nations Development Programme, Brussels. http://www.developmentminerals.org/images/pdf/Background-Study_EN.pdf (accessed 6th November 2018).

Hinton, J., Lyster, O., Katusiime, J., Nanteza, M., Naulo, G., Rolfe, A., Kombo, F., Grundel, H., MacLeod, K., Kyarisiima, H., Pakoun, L., Ngonze, C. & Franks D. M. (2018). Baseline Assessment of Development Minerals in Uganda Volume 1. In Franks, D. M., Pakoun, L. and Ngonze, C. (series editors), 'Development Minerals in Africa, the Caribbean and the Pacific'. ACP-EU Development Minerals Programme, United Nations Development Programme, Kampala. http://www.ug.undp.org/content/dam/uganda/docs/UNDPUg18%20-%20DevMinBaseLineUganda_Vol.1.pdf (accessed 6th November 2018).

Horlings, L.G. and Marsden, T.K. (2011) Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could "feed the world". Global Environmental Change, 21, 441–452.

IBRAM – Instituto Brasileiro de Mineração (2017) Relatório Anual de Atividades JUN/16 a JUN/2017 https://portaldamineracao.com.br/ibram/wp-content/uploads/2017/08/WEB_REL_IBRAM_2017.pdf, Accessed 18th September 2018

Ilchenko, W. (1955) Os tufos da Mata da Corda e seu emprego na Agricultura. Dep. Prod. Vegetal. Belo Horizonte, Boletim Agricultura, 9-10, 39 - 71.

Keeping MG (2017) Uptake of silicon by sugarcane from applied sources may not reflect plant-available soil silicon and total silicon content of sources. Frontiers in Plant Science. 8, 760.

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J., Pachepsky, Y., van der Putten, W.H., Bardgett, R.D., Moolenaar, S., Mol, G.., Jansen, B. and Fresco, L.O. (2016) The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals, Soil, 2, 111-128.

Lægrid, M., Bøckman O. C. and Kaarstad, O. (1999) Agriculture, Fertilizers and the Environment. CABI Publishing, Wallingford.

Leonardos, O. H., Fyfe, W.S. and Kronberg, B.I. (1976) Rochagem: O método de aumento da fertilidade em solos lixiviados e arenosos. Anais 29 Congr. Brasil. Geol., Belo Horizonte, pp. 137 – 145.

Leonardos, O. H., Fyfe, W. S. and Kronberg, B. I. (1987) The use of ground rocks in laterite systems – an improvement to the use of conventional soluble fertilizers. Chemical Geology 60, 361-370.

Leonardos, O. H., and Theodoro, S. C. H (1999) Fertilizing tropical soils for sustainable development. In: International workshop on Science for Sustainable development in Latin America and Caribe, 1999. Workshop on tropical soils. Rio de Janeiro: Academia Brasileira de Ciências 1, 143-153.

Leonardos O. H, Theodoro S. H. and Assad M. L. (2000) Remineralization for sustainable agriculture: A tropical perspective from a Brazilian viewpoint. In: Nutrient Cycling in Agroecosystems. 56, 3–9.

Manning, D. A. C. (2010) Mineral sources of potassium for plant nutrition: a review. Agronomy for Sustainable Development 30, 281-294.

Manning, D. A. C., Baptista, J., Sanchez Limon, M. and Brandt, K. (2017) Testing the ability of plants to access potassium in framework silicate minerals. Science of the Total Environment, 574C, 476-481.

Martins, E. de S., and Theodoro, S. H. (2010) Anais do I Congresso Brasileiro de Rochagem, Brasilia, 2009. Embrapa Cerrados, Planaltina, DF Brazil; 322 pp., ISBN: 978-85-7075-054-9.

Meena M. D. and Biswas D. R. (2014) Changes in biological properties in soil amended with rock phosphate and waste mica enriched compost using biological amendments and chemical fertilizers under wheat-soybean rotation, Journal of Plant Nutrition, 37, 2050–2073.

Melamhed, R., Gaspar, J.C. and Miekeley, N. (2009) Pó-de rocha como fertilizante alternativo para sistemas de produção sustentável. *In:* Lapido Loureiro, F.E et al. (Eds). Fertilizantes

Agroindustriais e Sustentabilidade. Rio de Janeiro, RJ, Brasil: Centro de Tecnologia Mineral, 2009, pp.385-396.

Mohammed, S. O., Brandt, K., Gray, N. D., White, M. L. and Manning, D. A. C. (2014) Comparison of silicate minerals as sources of K for plant nutrition in sandy soil. European Journal of Soil Science, 65, 653-662.

Nishanth, D. and D. R. Biswas (2008) Kinetics of phosphorus and potassium release from rock phosphate and waste mica enriched compost and their effect on yield and nutrient uptake by wheat (Triticum aestivum). Bioresource Technology 99, 3342–3353.

Palandri, J.L. and Kharaka, Y.K. (2004) A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling. U.S. Geological Survey Open File Report 2004-1068, Menlo Park, 64pp.

Priyono, J. and Gilkes, R. J. (2008) High-energy milling improves the effectiveness of silicate rock fertilizers: a glasshouse assessment, Communications in Soil Science and Plant Analysis, 39, 358-369.

Quisumbing, A. R. and Pandolfelli, L. (2010) Promising approaches to address the needs of poor female farmers: Resources, constraints, and interventions. World Development, 38, 581-592.

Ramezanian, A., Dahlin, A. S., Campbell, C. D., Hillier, S., Mannerstedt-Fogelfors, B. and Öborn, I. (2013) Addition of a volcanic rockdust to soils has no observable effects on plant yield and nutrient status or on soil microbial activity. Plant and Soil, 367, 419–436.

Ramos, C. G., Querol, X., Dalmora, A. C., de Jesus Pires, K. C., Schneider, I. A. H., Oliveira, L. F. S and Kautzmann, R. M. (2017) Evaluation of the potential of volcanic rock waste from southern Brazil as a natural soil fertilizer. Journal of Cleaner Production, 142, 2700-2706.

Römheld, V. and Kirkby, E. A. (2010) Research on potassium in agriculture: needs and prospects. Plant and Soil, 335, 155-180.

Sachs, J. D. (2003), Institutions Matter, but Not for Everything. Finance and Development, 40 (2) 38-41. From: https://www.imf.org/external/pubs/ft/fandd/2003/06/ (Accessed 20th September 2018).

Sachs, J. D. (2005) The End of Poverty – Economic Possibilities for Our Time, Penguin Press, New York, ISBN: 1-59420-045-9, 396 pp.

Santos, W.O., Mattiello, E.M., Vergutz, L. and Costa, R.F. (2016) Production and evaluation of potassium fertilizers from silicate rock. Journal of Plant Nutrition and Soil Science, 179, 547–556.

Sheldrick, W. F., Syers, J. K. and Lingard, J. (2002) A conceptual model for conducting nutrient audits at national, regional and global scales. Nutrient Cycling in Agroecosystems, 62, 61-67.

Siliprandi, E. (2014) Género y agroecología: los avances de las mujeres rurales Brasileñas enfrentando las inequidades. In: Siliprandi, E. and Zuluaga, G. P (eds.) género, agroecología y soberanía alimentaria perspectivas ecofeministas. Icaria Editorial. Barcelona. P 195-218.

Siliprandi, E. (2018) Mujeres rurales em América latina: organización y luchas por la dignidade campesina desde uma perspectiva ecofeminista. Boletin Eccos 42. 03 – 05/2018 Fuhen ecosocial (www.fuhen.es/ecosocial)

Smil, V. (2001) Enriching the Earth. MIT University Press, Boston MA.

Souza, M.E.P., Cardoso, I. M., Carvalho, A.M.X., Lopes, A. P., Jucksch, I. and Janssen, A. (2018) Rock powder can improve vermicompost chemical properties and plant nutrition: an on-farm experiment. Communications in Soil Science and Plant Analysis, 49, 1-12.

Tavares, L. de F., Mundstock, A., de Carvalho, X., Camargo, L. G. B., Pereira, S. G. de F. and Cardoso, I. M. (2018) Nutrients release from powder phonolite mediated by bioweathering actions. International Journal of Recycling of Organic Waste in Agriculture 7, 89-98.

Theodoro, S. H. and Leonardos, O. H. (2006) Sustainable farming with native rocks: the transition without revolution. Anais da Acad. Bras. de Ciências, 78, 715-720.

Theodoro, S. H. and Leonardos, O. H. (2014) Stonemeal: principles, potential and perspective from Brazil. In: Goreau, T. J., Larson, R. W. and Campe, J. Geotherapy: Innovative methods of soil fertility restoration, carbon sequestration and reversing CO_2 increase. CRC Press. USA. p. 403-418.

Theodoro, S. H., Martins, E. de S., Fernandes, M. M., Mundstock, A. and de Carvalho, X. (2013) Anais do II Congresso Brasileiro de Rochagem, Poços de Caldas, 2013; 399pp., Embrapa. ISBN: 978-85-8179.061-9.

Theodoro, S. H., Tchouankoue, J.-P., Gonçalves, A. O., Leonardos, O. and Harper, J. (2012) A Importância de uma Rede Tecnológica de Rochagem para a Sustentabilidade em Países Tropicais. Revista Brasileira de Geografia Física, 6, 1390-1407.

United Nations Population Division (2017) https://ourworldindata.org/future-world-population-growth/ (Accessed 25th May 2017).

van Straaten, P. (2009) Rocks for Crops, www.uoguelph.ca/~geology/rocks_for_crops, accessed 6th May 2018.

Vitousek, P. M., Naylor, R., Crews, T. David, M. B., Drinkwater, L. E., Holland, E. Johnes, P. J., Katzenberger, J., Martinelli, L. A., Matson, P. A., Nziguheba, G., Ojima, D., Palm, C. A., Robertson, G. P., Sanchez, P. A., Townsend, A. R. and Zhang, F. S. (2009). Nutrient imbalances in agricultural development. Science, 324, 1519-1520.

White, A.F. and Brantley, S.L. 1995. Chemical weathering rates of silicate minerals. Reviews in Mineralogy , 31, Mineralogical Society of America, Washington, USA.

World Bank (2018) Commodity prices. www.worldbank.org/en/research/commodity-markets, (Accessed 6th May 2018).

Mineral family	Mineral	Formula	Releases	Typical content	Dissolution rate $mol.m^{-2}s^{-1}$	Relative dissolution rate
Potassium silicates						
K-feldspar	Orthoclase	$KAlSi_3O_8$	K	14.1	-10.06	1
Feldspathoid	Leucite	$KAlSi_2O_6$	K	17.4	-6.00	11,500
Feldspathoid	Nepheline	$(Na,K)AlSiO_4$	K	4.2	-2.73	21,400,000
Mica	Muscovite	$KAl_3Si_3O_{10}(OH)_2$	K	9.1	-11.85	0.016
Mica	Biotite	$KMg_3AlSi_3O_{10}(OH)_2$	K, Mg	7.5, 3.6	-9.84	1.66
	Glauconite	$K(Fe^{3+},Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$	K, Mg	7.5, 3.0	-4.80	182,000
Other silicates						
Plagioclase	Anorthite	$CaAl_2Si_2O_8$	Ca	13.6	-3.50	3,630,000
Plagioclase	Albite	$NaAlSi_3O_8$	Na	8.7	-10.16	0.794
Olivine	Forsterite	Mg_2SiO_4	Mg	33.6	-6.85	1,620
Pyroxene	Wollastonite	$CaSiO_3$	Ca	33.6	-5.37	49,000
Pyroxene	Diopside	$CaMgSi_2O_6$	Ca, Mg	18.6	-6.36	5,010
Pyroxene	Enstatite	$Mg_2Si_2O_6$	Mg	35.0	-9.02	11
Amphibole	Hornblende	$Ca_2(Mg,Fe)_4Al[Si_2AlO_{22}](OH)_2$	Ca,Mg	8.6, 7.8	-7.00	1,150
Tourmaline	Dravite	$NaMg_3Al_6B_3Si_6O_{30}(OH)$	Mg, B	7.8, 3.5	-6.50	3,630

Table 1 Silicate mineral dissolution rate constants (25°C, pH = 0; Palandri and Kharaka, 2004). For comparative purposes, relative dissolution rates express the dissolution rate of a mineral relative to that of K-feldspar.